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Suitability of free space optical communication in military environments

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"Suitability of Free Space Optical Communication in Military Environments"

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Abstract

Free Space Optical (FSO) communications use modulated collimated light energy, usually in the form of an infrared (IR) laser, to transmit data. This affords FSO many appealing qualities such as a very high bandwidth capability, a high level of security through a low probability of detection (LPD) and a low probability of intercept (LPI), and a signal that is impervious to radio frequency (RF) interference or regulation. Military communications require broadband capabilities at the highest level of security in an incredibly dense RF operating environment. The bandwidth and security qualities of FSO make it an attractive technology for military communications. However, a strict line of sight (LOS) requirement and link attenuation in poor atmospheric conditions limit its application. Several companies and groups are developing and implementing FSO communication solutions worldwide in response to a demand for broadband connectivity without RF interference at a relatively low price point. Recent advances in hybrid FSO-RF systems have improved performance in all atmospheric conditions. This paper presents taxonomy of the current state of FSO communications systems and analyzes the suitability of FSO as a military communication solution. The findings indicate further research, development, and link performance improvement is required before most implementation of FSO communications can occur.

1. Introduction

Demand for bandwidth on the battlefield has increased significantly in the past 20 years. The introduction of full-motion video (FMV) via numerous different Intelligence Surveillance and Reconnaissance (ISR) systems such as targeting pods on aircraft, Ground Based Operational Surveillance Systems (GBOSS) towers, and Persistent Threat Detection Systems (PTDS) have increased the demand for network bandwidth considerably. The commander's desire to view these FMV feeds for areas even outside of their own battlespace triggered their availability to nearly everyone with access to the network.

Fiber-optic cable technology is more than capable of meeting this bandwidth demand. However, in most tactical networks it is not feasible to run cable from one node to another. In order to run and maintain the required cable, soldiers, sailors, marines and airmen would have to be placed in harm's way. Furthermore, securing the cable from the enemy would be a monumental undertaking. These factors and the high cost of laying cables make wireless communication methods the most favorable choice for tactical applications.

Current RF systems are not able to keep up with increasing bandwidth demands. For example, the AN/MRC-142C, is capable of streaming about 16 Mbps over a distance of roughly 50 kilometers [33]. This is sufficient for streaming FMV but not multiple feeds simultaneously with other data transmissions. The problem with bandwidth extends to ad hoc networking, where the number of nodes in a network is limited by the amount of bandwidth available. Furthermore, RF communications present a real challenge to security due to their high probability of detection and interception resulting from wide area propagation of the signal. Directed RF can be used to mitigate this to some degree but not to a level anywhere near that collimated laser energy. In addition, operating on RF signals requires deconfliction through the Federal Communications Commission (FCC) and adjacent units in RF dense operating areas.

Current terrestrial FSO systems are capable of delivering near fiber-like performance of 10 Gbps over a range of 50 km. Additionally, extraterrestrial FSO systems are capable of transmitting a 5 Gbps signal at distances of hundreds of thousands of kilometers. This performance gap over RF in bandwidth is accomplished by modulating eye-safe laser light. Utilizing laser light as a communication medium allows the user to accurately focus the transmission signal directly onto the intended receiver. This, in turn, offers a very high level of security through a low probability of detection (LPD) and low probability of interception (LPI). Furthermore, the FCC does not regulate laser light and the signal is much easier to deconflict than RF signals.

FSO technology has been slow to catch on. High cost combined with fairly high signal attenuation and low availability of early systems has tarnished the reputation of this technology. However, due to the potential available bandwidth and the absence of federal regulation, FSO is still seen as an attractive solution. Consequently, a great deal of money and time has been spent improving this technology. Advanced software and hardware techniques have improved link performance. Hybrid systems, those that incorporate an RF backup, have increased availability up to 99.999% even in unfavorable atmospheric conditions [34].

We investigate FSO communication systems as the solution to the military's bandwidth issues due to their high data rates, high level of security through LPI and LPD, and ease of use. This paper presents taxonomy of the current state of FSO communications systems and analyzes its suitability as a military communication solution. The findings indicate further research, development, and link performance improvement is required before most implementation of FSO communications can occur.

2. Background

The most common data communications in the U.S. military at the edge are tactical radio systems such as the Harris Falcon III family of Radios, which provides relatively low bandwidth compared to local area networks (LANs). The bandwidth demand in today's battle space continues to increase as more ISR sensors and networked information systems, especially as full motion video and high-density formats are introduced. Current RF wireless technologies are barely able to keep up with the bandwidth and range requirements of today's military digital communications. The AN/MRC-142C can stream 16 Mbps at a distance of 50 km, but with additional nodes and other users of that bandwidth the data rate will slow down much further, and in general the wider the broadcast footprint the greater the number of users who may transmit, and therefore the slower the resultant data rates. With the use of Manet and Ad Hoc networking, additional network overhead is required to support data delivery, further constraining network capacity, in addition each user on the network must send network data out to very user on the Manet network in order for each user to be found. Increases in network traffic due to increased battlefield activity causes network speeds to be at their worst just when the data would be most important. In order to deconflict radio waves, use of frequency managers are used and they must many times necessarily limit transmissions by some users. Anyone on a given RF channel has the ability to deny all users on that channel, while point-to-point transmissions, such as microwave, millimeter wave, and FSO only communicate on very narrow bands of physical space from between the endpoints.

2.1. Advantages of FSO

Optical communication does not have the problem where many users may share the same channel because FSO is primarily point-to-point communication allowing for much improved data rates, commercially available up to 10 Gbps at 1 km [28], and the data rate of FSO communication has been trending ever upward and the distances have been trending much greater. Theoretical limits of FSO can be quite high and allow for parallel additive channels. There are some other advantages to FSO communication other than higher data rates, and allowing for only two users at a time, such as: low probability of detection (LPD), and low probability of interception (LPI). Since the light is columnar and coherent there is very little diffraction and scattering to allow another user (an adversary) to detect the transmission and therefore to discover where communication occurs, therefore FSO is said to have LPD properties. Because FSO is LPD there is a very low probability for someone to insert a detector/transmitter in the middle of the beam to perform a man-in-the-middle attack, and because the speeds are so great, and communication is point-to-point, it would be hard to achieve, so FSO is said to have LPI properties. LPD and LPI have great benefit for clandestine operations, such as ISR. Another advantage of FSO occurs in space where there is no diffraction, absorption, scattering, or medium density turbulence.

2.2. Disadvantages of FSO

While the benefits of FSO are promising, there are many well-known problems. Some of the problems are due to atmospheric particulates, resulting in absorption, or scattering, and boundary layer problems due to temperature cause air density issues, and pointing and tracking of moving objects are difficult problems to solve. Some of these problems can be mitigated using hybrid -- dual wavelength systems such as using visible or near visible (nanometer) light spectrum with a backup of millimeter wave, or nanometer light spectrum along with RF. An example hybrid or dual wave system is the Aoptix millimeter wave and nanometer wave system, the nm light spectrum is fairly reliable in rain, while millimeter wave is fairly reliable in fog [19,20].

3. Survey and Taxonomy of FSO

Many commercial products were reviewed and an attempt was made to create an all-inclusive list of products that were applicable to distances greater than 1km, but some products may have been inadvertently left out. Of chief concern are products that are available currently and not in the future. Some FSO systems were based on contracts with different research organizations and as such we mention them for future reference, and due to the two categories we have broken down our assessment into current and near term future possibilities. A summary of results was created with Commercial product or Research Contract yielding published results vs. significant finding (see Table1). Note Table 1 is not the full list, but a summarized list from the results of the research [1].

3.1. Commercial FSO Systems

Most commercial products are trying to address either the last mile fiber optic problem, or trying to solve the mobile cell tower to fiber optic drop. Some commercial products are trying to solve the high volume data temporary network drop, which tend to be shorter distances, or Humanitarian Assistance, and Disaster Relief (HADR) and military. The air-to air and air-to-ground FSO systems tend to be much more expensive solutions as the pointing and tracking solutions depend on sophisticated equipment such as IMU's (Inertial Momentum Units that can cost $250k) [35].

3.2. Research FSO Systems

There have been and are currently several research contracts that have yielded published and important results worth mentioning, in the hopes that these products will become available for use in the future.

3.2.1. FALCON – Fast Airborne Laser Communications Node

The FALCON project was developed in collaboration with the Air Force Research Lab and ITT/Exelis in 2010. The experiment was successful at demonstrating a 2.5Gbps connection over an air-to-air link of 130km. We cannot determine what power this laser link was using, or if the laser was at an eye safe level. The rate and distance was achieved with the laser at half its maximum capability. Experiments were completed with air-to-ground links at similar rates and distances as the air-to-air experiments [2,3].

3.2.2. Talon -- Tactical Line-of-Sight Optical Network

The TALON project was developed in coordination with the Naval Research Laboratory with Exelis, Inc., and NovaSol (recently acquired by Corning). The research focus on TALON is networks from ship-to-ship and from ship-to-shore and resembles closely NovaSol's Compact Interrogator. The system has automatic acquisition, pointing, and tracking. The Compact Interrogator is optionally mounted on a 25-pound gimbal that permits unattended use and stabilization on mobile platforms. The system is entirely self-contained, requiring only power, Ethernet and gimbal control connections. This system is optimized for communications with miniature modulating retroreflector (MRR) terminals. When communicating with MRRs a 10 Mbps downlink and 2 Mbps uplink is achievable. However, direct interrogator-to- interrogator (DII) links are possible for multi-Gbps transmissions [34,4].

3.2.3. ViaLight and Airbus Defense and Space Experiment

Ongoing experiments have taken place with ViaLight, a commercial spinoff from DLR (German Aerospace Center, a German governmental research organization), and Airbus Defense and Space in November of 2013 [6]. The experiment used a Panavia Tornado jet plane traveling at 800 km/h (0.7Mach) and achieved continuous rates of 1.25 Gbps over a 50 km link [6,7]. If the link had line of sight (LOS) with the base station, then the link was active up to 50km. The position of the wings sometime broke the LOS, which accounted for most all the disruptions while the system was transmitting on the clear day, the partially cloudy days exposed significant drop off in link distance. The laser used was ViaLight's MLT-20 (micro laser terminal 20).

3.2.4. Aerostat To Ground Terminal Demonstration

In May 2006, AOptix and the John Hopkins University Applied Physics Lab demonstrated an FSO link between a tethered aerostat at an altitude of 1 km to a static ground station 1.2 km away. Using wave division multiplexing techniques data rates of 80 Gbps were achieved. An error free transmission of 1.2 Terabits was completed in 30 seconds at a rate of 40 Gbps. In all, 30 Terabits were transferred with an average BER of 10-6 without the use of forward error correction coding [8]. The success of this experiment led to the decision to mount two optical links aboard the USAF Big Safari Blue Devil Block II. The Blue Devil Air Ship was to act as a host platform in the Free-Space Optical Experimental Network Experiment (FOENEX) conducted by the Defense Advanced Research Projects Agency (DARPA). However, the Blue Devil project was cancelled in June 2012 [9].

3.2.5. LLCD – Lunar Laser Communication Demonstration

On October 18, 2013, NASA and the Goddard Space Flight Center's LLCD began to communicate optically from the moon at an error free rate of 622 Mbps. The link was also capable of a 20 Mbps uplink [10]. The transmissions continued for a total of thirty days. LLCD was done in conjunction with the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission. Massachusetts Institute of Technology's Lincoln Laboratory developed the LLCD ground terminal and flight system. There were a total of three ground stations, as shown in Figure 50. The European Space Agency (ESA) successfully communicated with the flight terminal from a ground station on Tenerife in the Canary Islands [11].

3.2.6. Tesat-Spacecom and US Navy NFIRE demonstration

The Tesat's LCT-135 is capable of transmitting 5.65 Gbps over a distance of 45,000 km. It was developed by the German company Tesat whose website is www.tesat.de. Since 2007, the LCT-125, the predecessor to the LCT-135, has been deployed on two satellites operating in low earth orbit. This is a joint operation between the United States, and its NFIRE satellite, and the German TerraSAR-X satellite. These two satellites have transmitted data between each other on multiple occasions setting a record of 5.6 Gbps. These transmissions occur at a distance of roughly 5,000 km at a speed of 25,000 km/h over duration of 20 minutes. Tesat hopes to incorporate this system into the European Data Relay System (EDRS). Eventually, Tesat would like to incorporate high altitude air ships and UAVs into the network as seen in Figure 48 [12 13].

Table 1 A Taxonomy of FSO Communications Systems (full list available in [1])

Static Systems	
Airlinx Communication Systems, Flight Strata XA	Static system, up to 5 km, Dual mode ability, minimum 70 Mbps to 1.485 Gbps, no auto tracking [24]
Aoptix SONAbeam 1250-M	1.25 Gbps at 4.8 km [25]
GeoDesy, PX 1000	1 Gbps up to 3.5 km [26]
LightPoint, AirBridge LX	1 Gbps up to 2.5 km, with hybrid upgrade [27]
Mostcom, Artolink	Auto-tracking (Russian), 10 Gbps 1.3 km, or 100 Mbps up to 3 km [28]
PAV Data Systems, PAVLight 155/Gigabit	155 Mbps at 4 km, or 1 Gbps up to 1km [29]
Plaintree Systems Inc, Wavebridge XT	2.048 Gbps up to 4km, can come in multiples up to 4x, so 8 Gbps up to 3 km [32]
SkyFiber Inc., SkyLINK	Hybrid RF minimum 100 Mbps, 1.25 Gbps up to 1.6 km [30]
Space Photonics, LaserFire	Auto-tracking, 1 Gbps up to 5 km, relatively small, less than 15min setup time to acquisition [31]
Dynamic: Systems Ground-to-ground	
Exelis and Nova-Sol (bought by Corning), Talon (US Navy, ONR Contract)	100 Mbps up to 50 km, optimized for use with Modulating Retro-reflector (MRR) providing 10 Mbps downlink and 2 Mbps uplink and optical switch [4,5]
Dynamic: Systems Air-to-ground	
ViaLight, MLT-20	1 Gbps up to 60 km at 800 km/h (Demo on Tornado Jet), base station currently is very large, Laser eye safe greater than 40m from aperture, is very light at 5 kg [23]

FSO Dynamic: air-to-air/air-to-ground	
Exelis, FALCON (USAF contract)	2.5 Gbps up to 130 km (information not provided as to whether laser is eye safe)
Aoptix and John Hopkins University Applied Physics Lab (DARPA Contract)	Aerostat to ground location achieved 80Gbps up to 1.2 km away [2]
RF Dynamic: Air-to-ground	
General Atomics Aeronautical Systems, GhostLink Radio Frequency Network (used for comparison of FSO to RF)	Comparison RF -- 80 Mbps over 180 km Ultra-wideband RF [14]

Dynamic: Space-to-space/Space-to-ground	
TESAT Spacecom, LCT-135	5.65 Gbps over 45,000 km, in addition space-to-space transmissions have been made at 5.6 Gbps up to 5000 km distance and a difference in speed of 25,000 km/hr between NFIRE (USN satellite) and TerraSar-X (German satellite) [12,13]
NASA Lunar Laser Communication Demonstration (LLCD)	622 Mbps download rate and 20 Mbps upload rate and a round trip of 238,000 miles from earth to the moon and back, note the computed network delay for distance alone is 1.52 sec, excluding any interface or component delay. Laser used was 0.5 Watt power [11,10,15]
Ball Aerospace Risley Prism	Beam Steering without pointing and tracking up to 120 degree field [16,17]
ViaLight MLT- 100	Still Under development, 1 Gbps at up to 600km, meant to be mounted on aircraft in the stratosphere and able to relay MLT-20 terminals located below [18]

4. Conclusions - Suitability of FSO to Military Environment

FSO communication is a viable solution for certain military applications. There are undeniable performance advantages of FSO over RF communications for certain scenarios under certain conditions. The modulated light of FSO is capable of supporting much larger bandwidths than radio frequencies. The collimated laser energy of FSO provides LPI and LPD properties, which is desirable for security and clandestine operations. FSO's immunity to RF interference makes the signal resilient to jamming and allows operation without frequency deconfliction. These benefits are significant for military communications where a great deal of money is spent on equipment and software and effort expended securing RF communications usually resulting in degraded link performance. However, there are also considerable limitations to FSO that prevent it from being a direct replacement for all RF communication links. These limitations are atmospheric interference, which is a very considerable problem for FSO communications, a strict LOS requirement, and a limited ability to conduct area transmissions.

The performance of an FSO link is directly correlated to the atmospheric conditions within which it is operating. Particulates in the air, turbulence and irregular air density all impact FSO link performance. For this reason, it is difficult to accurately determine how FSO will perform in a given environment over time until it can actually be tested in that environment for an appropriate period of time. This is also true for RF communications, but the effect that atmospherics have on FSO is much greater than on RF. This is very concerning when considering FSO as a communication solution where high-availability in all weather conditions is a priority. Implementing a hybrid dual mode FSO-RF, or FSO-millimeter wave solution can mitigate link degradation in unfavorable atmospherics. However, in doing so the LPI/LPD and RF immunity of the link is compromised. Additionally, there are several possible applications of FSO where adverse atmospherics will most likely not be encountered. These include space applications, high altitude air-to-air links and on UAVs that are only capable of operating in visual meteorological conditions (VMC) due to ISR sensor and/or aircraft limitations.

The requirement for LOS is the biggest limitation to FSO because it will simply not operate without it.

Establishing LOS in tactical situations can be difficult and dangerous as it usually involves elevating and exposing the transceiver, the operator or both. Due to the LOS limitation, FSO systems are most suitable for static ground-to-ground, static ground-to-air, air-to-air and space applications. The LOS requirement makes FSO unsuitable for dynamic ground-to-ground and marginal for dynamic ground-to-air links, except in applications that only require very short transmission ranges. There are too many obstacles encountered between two moving ground stations and between a moving ground station and an airborne platform. The exceptions to this are FSO links between surface ships, between a surface ship and an airborne platform and for ship-to-shore communications. The open sea provides a relatively obstacle free environment across its surface. However, links over the ocean eventually fall victim to the LOS requirement due to the curvature of the Earth.

The collimated laser energy used in FSO communications aids in the security of the link through LPI and LPD, but is not effective in disseminating information to multiple receivers. The only way to transmit, from a single transmitter, over an area is by increasing beam divergence. As beam divergence increases, the range of the link decreases. Currently, FSO is not suitable for applications requiring the dissemination of information to multiple dislocated nodes from a single source.

When considering what environment works well with what FSO device it is important to consider whether the user is static or dynamic, typical distance, where the typical network data path lies, and any interdicting problems with existing infrastructure.

4.1. Within Base

One of the most promising military environments for an FSO system is within a military base. Currently many bases use fiber optic or cat5 ground cabling which is subject to disruption due to movement of motorized equipment around the base, in addition when a base is reconfigured or moved the ground wires are removed and thrown away and accounted for as sunk cost. Much of the commercial last optical mile equipment, especially the hybrid equipment, would seem ideal for use on bases because the endpoints remain relatively static, and this should achieve a faster initial uptime and should result in faster re-establishment of network connectivity in case of damage due to conflict or disruption. Space Photonics LaserFire system shows promise in quick setup, light weight, and low power, but in a demonstration performed at Camp Roberts, CA, there where some shortcomings as far as plug and play for suitability in a military base setting, but these short comings could possibly be remedied by Space Photonics in the near future [1]. Many of the other static FSO commercial products may prove very useful for bases. A study should be performed to determine which network legs should be replaced by FSO and then a pilot program of FSO replacement could be implemented as the next logical steps to determine FSO suitability on military bases.

4.2. Between Bases

Another near term use case for FSO is between bases where bases are co-located within 2-4 km of each other, which may be likely in tactical zones. These bases may need high towers to create a line of sight for FSO to work. Many of these tactical bases have surveillance towers such as Ground Based Operational Surveillance Systems (GBOSS), which could also serve as ideal locations to mount FSO systems to increase bandwidth, another benefit is the reconnaissance feeds of the two bases could possibly be shared.

For bases that are greater than 5 km, but less than 50 km apart the TALON project may be able to provide connectivity in the not too distant future.

Another possibility to increase communication and surveillance between bases further than 4 km is to use of aerostats with FSO attached. This may be a promising field of research.

4.3. Ship-to-Ship

Ship-to-Ship communication may be another area where FSO could be used. The distances are not great but due to the likelihood of rain or fog a hybrid FSO system may be the best choice. The NovaSol system demonstrated this capability in the Trident Warrior 2008 (TW08) exercise at less than one watt for hundreds of Megabits per second data rates [36]. This system is a hybrid RF FSO and uses a camera to achieve optical lock prior to FSO communications [37]. The DoD is active in this research Aoptics in 2004, and others, and TALON currently [22].

4.4. Ship-to-Shore

A TALON like hybrid system may be of benefit from ship to shore. TALON is currently going through testing with coalition forces and will have RIMPAC 2016 and Trident Warrior 2016 test data in the next half year. TALON is not available for current deployment, but shows promise in establishing networks from ship-to-shore. To establish a more typically ship-to-shore spaced network there may need to be relays from many miles out at sea using UAS, or extended height buoys to rise above wave action. Once to shore, the networks could then be extended further inland via a relay of TALON, or other FSO devices.

4.5. Tactical Edge

Another military future environment for FSO use is in air-to-ground networks. ViaLight's MLT-20 demonstration providing a 1.25 Gbps 60 km network from a Tornado jet plane traveling at 800 km/h to a ground source provided proof of technical feasibility of FSO air-to-ground capability [6,7]. ViaLight is working on the ground station and should be ready for a commercial solution in 2015 [35]. The distances could be extended using a combination of aerial and ground relays along with unmanned aerial systems (UAS). The possibility of using FSO to de-conflict RF traffic may maximize bandwidth. The best methodology that may bring the best results is a hub and spoke architecture where the spokes would be localized RF and hub backbone would be FSO. By keeping the localized elements talking over localized RF and the backbone traveling over the FSO network the radio channels are kept clear for localized data. Due to the static nature of current technology this ability is not ready to deploy at present, but may be within the next 5 years.

4.6. Ground Sensors

The hub and spoke method is very attractive for ground sensors that can provide a lot of data throughput; such sensors are starting to proliferate the battle space [21]. Future research in sensor design may consider FSO in the non-visible spectrum for communication to retain sensor secrecy during transmission. The hybrid array could be an RF Manet network feeding into an FSO network. For an adversary that can detect RF, use of FSO networking amongst the sensors and reach back may be needed to sustain total secrecy. More research is needed in this area.

5. Acknowledgements

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